

(19)



(11)

EP 1 413 023 B1

(12)

EUROPEAN PATENT SPECIFICATION

(45) Date of publication and mention
of the grant of the patent:
29.08.2007 Bulletin 2007/35

(21) Application number: **02749077.0**

(22) Date of filing: **29.07.2002**

(51) Int Cl.:
H01S 5/0625^(2006.01)

(86) International application number:
PCT/GB2002/003463

(87) International publication number:
WO 2003/012936 (13.02.2003 Gazette 2003/07)

(54) **TUNEABLE LASER**

ABSTIMMBARER LASER

LASER ACCORDABLE

(84) Designated Contracting States:
DE FR GB

(30) Priority: **30.07.2001 GB 0118412**
17.10.2001 GB 0124921

(43) Date of publication of application:
28.04.2004 Bulletin 2004/18

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Description

[0001] This invention relates to tuneable lasers and has particular, but not necessarily exclusive, reference to tuneable lasers for use in telecommunications systems operating in the C-band, namely within the band of 1530 to 1570 nm. The embodiments concern in particular, but not exclusively, four section distributed Bragg reflector tuneable lasers.

Background to the Invention

[0002] In this specification the term "light" will be used in the sense that it is used in optical systems to mean not just visible light but also electromagnetic radiation having a wavelength between 1000 nanometres (nm) and 3000 nm.

[0003] Single wavelength lasers are important for a number of applications in optical telecommunications and signal processing applications. These include multiple channel optical telecommunications networks using wavelength division multiplexing (WDM). Such networks can provide advanced features, such as wavelength routing, wavelength conversion, adding and dropping of channels and wavelength manipulation in much the same way as in time slot manipulation in time division multiplexed systems. Many of these systems operate in the C-band in the range 1530 to 1570 nm.

[0004] Tuneable lasers for use in such optical communications systems, particularly in connection with the WDM telecommunication systems, are known. A known tuneable system comprises stacks of single wavelength distributed Bragg reflectors (DBR) lasers, which can be individually selected, or tuned over a narrow range, or by a wide tuning range tuneable laser that can be electronically driven to provide the wavelength required. Limited tuning range tuneable lasers that rely upon thermal effects for tuning are also known.

[0005] US-A-4896325 discloses a wavelength tuneable laser having sampled gratings at the front and rear of its gain region. The laser described in that specification relies on the use of two different gratings which produce slightly different reflection combs in the front and rear gratings. These provide feedback into the device. The gratings can be current tuned in wavelength with respect to each other. Co-incidence of a maximum from each of the front and rear gratings is referred to as a supermode. To switch the device between supermodes requires a small incremental electrical current into one of the gratings to cause a different pair of maxima to coincide in the manner of a vernier. By applying electrical currents to the two gratings so that the corresponding maxima track, continuous tuning within a supermode can be achieved. US 5,379,318 describes a similar wavelength tuneable laser.

[0006] In summary, for a given set of drive currents in the front and rear grating sections, there can only be a simultaneous correspondence in reflection peak at one

wavelength, as a consequence of which the device lases at that wavelength. To change that wavelength a different current is applied to the front and rear gratings. Thus the front and rear gratings operate in a vernier mode, in which the wavelengths of correspondence determine a supermode wavelength.

[0007] An improved form of selective grating is the phase shifted grating, as described in GB-A-2 337 135.

[0008] The term "phase shifted grating" as used herein is used to describe and define a selectively reflecting distributed Bragg grating which is constructed and operates in the manner described and claimed in GB-A-2 337 135. In other words, a phase shifted grating is one in which the grating structure comprises a plurality of repeat gratings in which each grating unit comprises a series of adjacent diffraction gratings having the same pitch, and is characterised in that the grating units and adjacent gratings within a grating unit are separated by a phase shift of substantially π (pi) radians and in which at least two of the gratings within a grating unit have different lengths, the lengths being selected so as to provide a predetermined reflection spectrum.

[0009] Details on the construction and operation of the phase shifted grating are to be found in GB-A-2 337 135.

The Bragg gratings may be defined using e-beam writing onto suitable photoresist as a processing step.

Summary of the Invention

[0010] By the present invention there is provided a tuneable laser having a gain section bounded at one end by a first reflector in the form of a distributed Bragg reflector adapted to produce a comb of reflective peaks and on the other end by a second Bragg reflector, the second Bragg reflector adapted to reflect at a plurality of wavelengths and being capable of being varied selectively through discrete segments so that one or more segments of the Bragg reflector can be tuned to a lower wavelength to reflect with a segment reflecting at that lower wavelength to enhance the reflectivity at that lower wavelength.

[0011] The lower wavelength to which the second reflector is tuned may substantially coincide with a peak of the first reflector.

[0012] The second reflector may be formed in a material having a variable refractive index and the variation of the reflected wavelength may be affected by varying the refractive index of the material.

[0013] The refractive index may be varied by passing an electrical current via electrodes through the material in which the second reflector is formed.

[0014] The second Bragg reflector may be a chirped grating and may be formed in a material having a refractive index variable in response to the passage of current therethrough, there may be a plurality of external electrodes along the length of the grating, with each electrode being selectively connectable to a power source.

[0015] The second Bragg reflector may comprise a plu-

ality of discrete grating segments, at least two of which grating segments may have a different pitch wherein current may be applicable to at least the grating having a longer pitch such that the effective wavelength of the grating having a longer pitch can be tuned to the wavelength of the grating having a shorter pitch.

[0016] The chirped Bragg reflector may comprise a linear chirp of progressive pitch variation along the chirp with the shortest pitch closest to the gain section.

[0017] The second Bragg reflector may comprise a plurality of discrete grating segments, each grating segment having a different pitch, such that the grating segment closest to the gain section has the shortest pitch, the pitch of each successive grating segment from the gain section may be greater than the pitch of the preceding segment.

[0018] Each grating segment may have an independently actuatable electrode.

[0019] A switching circuit may be provided to switch the current to the electrodes.

[0020] The tuneable laser may be manufactured using semiconductor materials, particularly using a III-V semiconductor material. It may be manufactured using electron beam writing techniques or may be manufactured using a holographic phase grating plate.

[0021] The Bragg segments in the second reflector may be each kept short so that the cumulative waveguide length associated with the Bragg gratings is minimised, thereby keeping the waveguide attenuation losses low.

[0022] The distributed Bragg reflector forming the first reflector may be a phase shifted Bragg grating reflector, and light may be emitted through the second reflector.

[0023] There may be a phase change section between the gain section and either one or both of the reflectors.

[0024] The phase change section may be located between the gain section and the first reflector.

[0025] Alternative arrangements of the segmented grating order are possible within the scope of the invention.

[0026] Alternative arrangements of the chirp are possible for example, a non linear progressive chirp, and the longest pitch being closest to the gain section.

[0027] In the case where the second reflector is a chirped Bragg reflector it may be considered as being partitioned into chirp segments each consisting of part of the over all chirp grating, all chirp segments being concatenated.

[0028] Other means of varying the refractive index than a current could be used, for example by thermal means, or use of an electric field.

[0029] By short Bragg segments is meant lengths such that the associated reflectivity of each segment is broad and there is a degree of overlap between neighbouring segment reflectivities. However, the segment reflectivity discrimination is sufficient for stable lasing operation in combination with reduced light power losses.

[0030] In one embodiment the first reflector comprising a distributed Bragg reflector which is made long as herein defined.

[0031] "Long" as used in this context herein means as many repeat grating units, as described in GB-A-2 337 135, as are required to produce sufficiently narrow peaks for single longitudinal mode operation of the laser. Preferably 10 or more repeat grating units are present.

[0032] The first reflector may also have an electrode to permit electrical current to be passed through it to alter the wavelengths at which the comb of reflecting peaks reflects.

[0033] The phase change section(s) may have an electrode(s) to permit the passage of electrical current through the phase change section(s) to alter the refractive index of the material of the phase change section(s) to affect the phase change.

[0034] The refractive index of the material in which the front and rear Bragg gratings are formed is variable simultaneously to affect fine tuning of the laser.

[0035] The distances between the electrodes on the second reflector are short as herein defined.

[0036] The grating of the first reflector may be long so as to produce reflection peaks at well defined wavelengths.

Brief Description of the Drawings

[0037]

Figure 1 is a schematic cross section through a laser in accordance with the invention incorporating a segmented Bragg second reflector,

Figures 2a to 2e are graphs of intensity I vs. wavelength λ , for the segmented Bragg second reflector embodiment,

Figure 3 is a schematic cross section through a laser in accordance with the invention incorporating a chirped Bragg second reflector,

Figure 4 shows a second embodiment of the invention,

Figure 5 shows a chirp grating,

Figure 6 shows a chirp line,

Figure 7 shows an enlarged view of light passing down a chirp grating,

Figures 8 and 9 show box diagrams of light intensity vs wavelength,

Figure 10 is an explanatory view of a chirp laser chirp line and light intensity,

Figures 11 and 12 shows chirp line drawings, and Figures 13a to 13e are graphs of intensity I vs. wavelength λ , for the chirp Bragg second reflector embodiment.

Description of the Preferred Embodiments of the Invention

[0038] The wavelengths of interest referred to above, for example the C-band wavelengths of 1530 to 1570 nm are the wavelengths of light in free space. When such light passes through a medium, of refractive index n_{eff}

the actual wavelength of the light within that medium, which will be referred to herein as λ' , is the wavelength λ divided by the value for the refractive index N_{eff} . In other words

$$\lambda' = \lambda / N_{\text{eff}} \quad (1)$$

where N_{eff} is the effective refractive index of the medium as seen by the propagating light of wavelength λ in free space.

[0039] It so happens that the glass (silica) fibres, which are commonly used in telecommunications systems, have low loss regions at about 1100 nm, 1300 nm and 1500 nm. These regions are about 100 nm wide and consequently much work is done on producing lasers that produce light in the low loss bandwidths. The same is true for the tuneable laser of the present invention. The specific examples of the invention are designed to work in the c- Band, but the invention could be used for other wavelengths if required and if new types of fibre optical cables become available.

[0040] Referring to Figures 1 and 3, they show schematic cross sectional views of a lasers in accordance with the present invention. As is conventional in semi-conducting lasers the laser is built up in a series of layers, with a layer 1 formed between a lower layer 2 and an upper layer 3. Layer 1 bounded by layers 2 and 3 forms a waveguide. There may be a plurality of layers in the structure, but they are not material to the invention and for the better understanding of the invention they are not shown.

[0041] In Figure 1 the laser itself has four principal sections. A gain section 4, a phase change section 5 and front and rear reflecting sections 6 and 7. The rear reflecting section 7 has a phase shifted grating distributed Bragg reflector 8 formed in the layer 3. Such a reflector produces comb of reflectance peaks at separated wavelengths, and each peak is of substantially the same height. The front reflector 6 is made up of a series of segments, each segment being a distributed Bragg reflector, each segment centred at substantially a single wavelength with a broad wavelength reflecting spectrum. The centre wavelengths of the individual peaks of the segments 9 to 16 correspond to the peaks of the comb of reflectance produced by the front reflector distributed Bragg reflector.

[0042] In Figure 3 the laser itself has four principal sections. A gain section 61, a phase change section 60 and front and rear reflecting sections 62 and 50 respectively. The rear reflecting section 50 has a phase shifted grating distributed Bragg reflector 51 formed in the layer 3. Such a reflector produces a comb of reflectance peaks at separated wavelengths, and each peak is of substantially the same height. The front reflector section 62 consists of a linear chirped grating of progressive pitch variation along the length. Above the chirped grating are a series

of individual adjacent electrodes 65 through 72, that define sub-region chirped gratings that together comprise the over-all chirped grating. Each of the sub-region chirped gratings reflects over a range of wavelengths. In its passive state the total reflection spectrum covers the band of interest with substantially uniform reflectivity.

[0043] The invention design may be suitably applied to solid-state lasers manufactured using Group III-V or other semiconductor materials.

[0044] In the case of the segmented Bragg grating front reflector four section laser, the method of operation of the laser is more readily understood by reference to Figures 2a to 2e. These drawings show aligned one above the other the combs of reflectance produced by the front and rear reflectors. In the drawings the intensity of reflectance I is plotted vertically against wavelength λ . Fig 2a shows the comb of reflectances 29a to 36a produced by the segmented gratings 9 to 16 when no current is applied to any of the electrodes 9a to 16a. The comb peaks are broad due to the Bragg grating segments being short. This comb is positioned directly over the comb of reflectances 39a to 46a shown in Figure 2b, which is produced by the rear grating 8 in the laser. It can be seen that the peaks 29a to 36a substantially coincide in wavelength with the wavelengths of peaks 39a to 46a.

[0045] If just sufficient current is injected into the gain section to make it generate light, the laser will not lase because the intensity of the light at all of the wavelengths represented by the peaks 29a to 36a (and of course all other wavelengths) is below the lasing threshold.

[0046] To get the laser to lase predictably, it is necessary to have both a population inversion of charge carriers within the gain material and to get at least one, and preferably only one, wavelength to be above the lasing threshold. This is achieved by injecting 'sufficient current into the gain section 4 through electrode 4a to create the population inversion and by making a portion of the front grating reflect light of a specific wavelength preferentially, so that the rear grating selectively reflects light of that particular wavelength. The front grating will reflect back the light of that wavelength so that that wavelength will become the preferred or enhanced wavelength and the laser will commence to lase at that wavelength.

[0047] This is carried out as follows.

[0048] The material of which layer 3 is formed in the sections corresponding to the reflectors 6 and 7 is such as to experience a reduction in refractive index when an electrical current is passed through it. Thus if a current is passed through the electrode 12a, the wavelength at which the Bragg reflector in segment 12 reflects light will be reduced. If the reduction is such that it now reflects light at the same wavelength as the Bragg reflector of the adjacent segment, segment 11, then the arrangement shown in Fig 2c will occur. The intensity of the peak 31a as shown in Fig 2a is reinforced such that it is much higher as shown at A in Fig 2c and more intense than the peaks 29a 30a, and 33a to 36a. As a consequence, peaks 32a of Fig 2a is reduced as shown at B in Fig 2c.

[0049] Now if current is also passed through the electrode 4a to create light in the gain section 4 at an intensity above the lasing threshold, the light at wavelength corresponding to the peaks 31 a and 41 a is selectively reinforced and the laser will commence to lase at that wavelength as shown at C in Figure 2d. Thus the laser will be tuned to that wavelength. An advantage of this laser design is that the breadth of the front reflector peak can be sufficiently broad that tuning may be affected solely by the rear grating tuning current, within the wavelength window defined by the broad front reflector peaks.

[0050] If a current is then also passed through electrode 7a this will effectively move the whole comb of peaks 39a to 46a including peak D to lower wavelengths as shown in Figure 2e. The peak D will have a slightly reduced intensity compared to peak C because the maxima of the peaks of the front and rear reflectors are no longer exactly aligned.

[0051] If at the same time a current is passed through electrode 11 a and the current passing through electrode 12a is increased, then the peak 31a in Fig 2a will also move to a lower wavelength and thus the maxima of the peaks of the front and rear reflectors can be brought back into exact alignment.

[0052] Thus the laser can be fine tuned to lase at wavelengths between the peaks 39a to 45a as shown in Fig 2b by either of the two operations.

[0053] It will be appreciated that as the peak 35a cannot be moved to longer wavelengths by this method, the longest wavelength at which the laser can lase is substantially that of peak 45a as shown in Fig 2d.

[0054] To ensure complete band coverage out of band, or edge-of-band, segments can be employed. The long wavelength out-of-band segment being provided with a tuning electrode so that it can, by means of current injection, be driven to coincide with the first in-band long wavelength segment. The short wavelength out-of-band segment does not of necessity need to be provided with an electrode as its operation, as this lasing wavelength, is determined by driving current into the shortest wavelength in-band segment. The short wavelength out-of-band segment does need to be provided with an electrode if required to be fine tuned.

[0055] Incorporation of these out-of-band, or edge-of-band segments allows for production spread in operating characteristics and helps improve production yields.

[0056] With InP, as a typical Group III-V laser material the reduction in material refractive index through current injection permits wavelength tuning in the range of 1 - 10nm. Using such material the tuning segments will typically be designed at 4nm wavelength spacing. With such an arrangement to produce coincidence with its next lowest wavelength neighbour requires 4nm wavelength shift of a segment, whilst leaving a further 4nm coincident tuning capability. By this means the whole band of interest may be covered.

[0057] In the case of the chirped grating distributed Bragg front reflector the method of operation of the chirp

section is more readily understood by reference to Figures 3 to 12.

[0058] Referring to Fig 3 this shows an alternative form of the invention in which the discrete Bragg grating sections 9 to 16 of Fig 1 are replaced with a chirp grating. The laser assembly includes a rear reflecting section 50 similar to rear reflecting section 7 of Fig 1 and having a phase shifted Bragg grating 51, a gain section 61 a phase change section 60 and a chirp grating section 62. Located on the gain section 61 is an electrode 64 to enable the passage of current into the gain section. Located on the rear reflecting section 50 is an electrode 52 and on the phase change section 60 is an electrode 63 to enable the passage of current into the rear reflector and phase change sections respectively. Located on the chirp Bragg section is a series of individually selectable electrodes 65 to 72 to permit current to be passed selectively into portions of the chirp grating within section 62.

[0059] The chirp grating is a form of Bragg grating which has a substantially continuous variation in the wavelength at which it reflects light along its length. It is thus distinguished from a normal distributed Bragg reflector (DBR) which reflects at a single peak wavelength and also from a sampled grating DBR, which reflects at a plurality of discrete wavelengths.

[0060] A chirp grating is formed at the interface between two materials of different refractive index and can be represented graphically as a sinusoidal shaped waveform, or as a castellated form. The physical shape of the grating is dependant upon the etching technique employed and may result in a castellated form, particularly when a dry etching process is used to produce the grating, e.g. reactive ion etching.

[0061] The refractive index, n , of the material used in the production of the chirp grating through which the majority of the light passes is a quaternary material (In-GaAsP) and the refractive index of the material varies with the wavelength of light passing through the material. Typically n at 1570 nm is 3.33, at 1550nm n is 3.38 and at 1530nm n is 3.43. Thus n decreases by about 3% from 1530 nm to 1570 nm.

[0062] An explanation of the construction and operation of the chirp grating is provided by Figures 4 to 12.

[0063] As shown in Figure 5 the grating is formed as an interface 80 between the upper layer of material 81 of a low refractive index and a lower layer 82 of a higher refractive index. This interface can be represented as a waveform and the pitch Λ of the waveform making up the grating is gradually increased along the length of the grating from Λ_s at the short end of the chirp grating to Λ_L at the long end of the grating. In Fig 5 the increase in pitch is deliberately exaggerated to demonstrate what is happening. In practise the increase in pitch length over the whole of the grating is small, namely about 2.5%, so that at the short end the grating reflects light of a wavelength of about 1530 nm and at the long end the grating reflects light at a wavelength of 1570 nm. Thus there is a 40 nm variation in the reflection wavelength over the length of

the grating, which is about 2.5% of the average wavelength of 1550 nm.

[0064] In Fig 6, there is a graph showing how the pitch of the grating varies along its length with the pitch Λ in the vertical axis and the length of the grating x on the horizontal axis.

[0065] It will be appreciated that the pitch values, Λ , along the length of the grating can be plotted directly against the length and a line is generated. The line can be straight or can be curved depending on how the pitch length is varied along the length of the grating. If the increase in grating pitch is at a constant rate the line is straight as shown at 83a, and the grating is called a linear chirp grating. If the increase in grating pitch along the grating is uniform, in other words in the direction of increasing Λ , each Λ is a certain small constant step increment on the one before it, then the line will not be linear but will curve downwards as shown at 83b, as the line increasingly goes to the right. Other increases in grating pitch along the grating will produce different curves.

[0066] Referring to Figure 7, this demonstrates the effect of light passing along a chirp grating. Again the grating is shown as a sinusoidal interface 84 between an upper layer 85 of a lower refractive index and a lower layer 86 of higher refractive index. The waveguide of the assembly of high refractive index through which the majority of the light passes is shown at 87, separated from the lower layer 86 of the chirp grating by an intermediate layer 88 of low refractive index. Underneath the waveguide 87 is a further low refractive index substrate 89. Superimposed on the layer structure is a graphical representation of the wavefront of the light passing through from left to right as at 90 in the direction of the arrows 91. Line 92 is an indication of the intensity of the light in the layers of the assembly and it can be seen that most of the light passes through in the waveguide of high refractive index.

[0067] As shown in Figure 7, the light passes not only through the waveguide but the evanescent wave also passes along the layer 86 forming the lower layer of the chirp grating. If the light should happen to have a wavelength λ' which is twice the length of a pitch Λ then that light will be reflected back i.e. if $\Lambda = 2\lambda'$ then that wavelength of light will be reflected. Thus the chirp grating as a whole will reflect light in the range $\lambda'_S = 2\Lambda_S$ to $\lambda'_L = 2\Lambda_L$ where Λ_S is the shortest grating pitch and Λ_L is the longest grating pitch. Light of wavelengths outside of this range will not be reflected back along the waveguide.

[0068] This can be represented diagrammatically as in Figs 8 and 9, which are box diagrams of intensity of light I in the vertical axis and wavelength λ' in the horizontal axis. If a box of light of plurality of wavelengths is admitted into the grating as shown at 93 in Fig 8, the envelope is complete and represents all of the wavelengths between λ'_1 and λ'_2 which are widely separated wavelengths. However as the chirp grating reflects certain of the wavelengths, for example between λ'_S and λ'_L in Fig 5, the emerging box of wavelengths 94 as shown

in Figure 9 has a gap 95 which corresponds to those wavelengths between λ'_S and λ'_L reflected by the chirp grating.

[0069] The chirp grating will, if in its complete and unaltered condition, reflect all wavelengths between λ'_S and λ'_L without any preference. However if one of the electrodes such as electrode 68 of Figure 10, has a current passed through it, then that will lower the refractive index of the material in which the chirp grating is created. This will result in the grating as a whole being selectively enhanced in its reflectivity at an adjacent lower wavelength specific wavelength and this can result in the laser lasing at that wavelength.

[0070] This will be explained below in greater detail with reference to Fig 10. In this figure the upper portion shows the laser of Figure 4. This is positioned over the chirp diagram (as shown in Fig 6) which in turn is positioned over a drawing of the reflectivity of the chirp grating vs distance.

[0071] It can be seen in the central portion of Fig 10, where the grating pitch Λ is plotted against distance x , that the chirp response line is shown by a line 96. It will be seen that line 96 has a region 98, shown dotted below the main portion of the line, for reasons which will be explained below.

[0072] On the outer surface of the laser there are a series of electrodes 63 to 72. The electrode 64 can be used to inject current into the gain section to make it create light. The electrode 63 can be used to control the phase section as described below and the electrodes 65 to 72 are able to inject current into different regions of the grating 62.

[0073] If just sufficient current is injected into the gain section to make it generate light, then if the chirp section is capable of reflecting light in the range of 1530 to 1570 nm the wavelengths of light within that range will be internally reflected. Light outside of the reflecting wavelengths will be absorbed or will be emitted from the ends of the laser. The laser will not lase because the intensity of the light at all of the frequencies in the range 1530 to 1570 nm is below the lasing threshold.

[0074] The selection of a particular wavelength at which the chirp grating will reflect is affected by passing a current through an electrode such as electrode 68 above the portion of the chirp grating which corresponds to the region 98 in the chirp curve 96. The effect of the passage of current is to increase the current density in that region of the grating, which lowers the refractive index of the grating layer 86 just below the electrode 68. The lowering of the refractive index has the effect of making the grating reflect at a lower wavelength, which is the same effect as would be obtained by shortening the grating pitches in that region.

[0075] This means that the effective grating pitches of the dotted portion 99 as is shown in the central portion of Figure 10 now line up with the adjacent region 97, forming a chirped Fabry-Perot étalon, which thus reinforces the reflection in the adjacent region 97.

[0076] Referring to the lowest portion of Figure 10, which is a graph of reflectivity 11 vs. distance x, it can be seen that there is a trough 98A in the reflectivity of the grating which corresponds to the region 98 that now reflects at a lower wavelength. However there is now an enhancement of the reflectivity of the region 97 due to the resonant chirped Fabry-Perot étalon structure. Thus there is produced the reinforced peak 97 A in the reflectivity.

[0077] Light at the wavelength that corresponds to the position of peak 97A is thus selectively reflected.

[0078] It will be appreciated that without any further adjustments, the reflection characteristics of the chirp grating could only be adjusted to as many different wavelengths as there are electrodes 65 to 72.

[0079] However, the grating can be made continuously adjustable if it is assumed that the materials from which the chirp gratings are constructed have a sufficiently variable refractive index.

[0080] Fig 11 illustrates how this can be put into effect. In Fig 11 there is shown the chirp grating which acts as a mirror under three different conditions.

[0081] In the drawing there are shown ten electrode positions 100 to 109, which correspond to the electrode positions 65 to 72 in Figure 10. In other words, instead of there being eight electrodes over the rear grating, there are ten electrode positions in this schematic. The line 110 corresponds to the line 96 of the grating as shown in Fig 10. The vertical dotted lines show the alignments of the electrodes and the portions of the chirp diagram.

[0082] In the upper portion of the Fig 11 there is no current flowing through any of the electrodes 100 to 109. The line 110 is continuous with no portion being preferred.

[0083] In the central portion of Fig 11 a current is passed through electrode 106. The current being half that required to cause the maximum reduction in the refractive index of the material of the chirp grating below the electrode 106 which is equivalent to material 86 in Fig 10. The result of this is to displace downwards the portion 111 of the line 110. This results in a selection of a particular wavelength at which the chirp grating reflects in exactly the same manner as described above with reference to Fig 10.

[0084] To further adjust the grating, so as to reduce the wavelength at which reflection occurs, current is passed through all of electrodes 100 to 105 and at the same time the current passing through electrode 106 is increased. This causes a lowering of the portion 112 of the chirp line below its original position, shown dotted. The portion 111 a of the line 110 also is lowered at the same time, thus moving the point of selection to a lower wavelength. In best practice no additional current need be passed through electrodes 107 to 109, as they play no part in the reflecting process. However, since they play no part in the selection process, it is possible for the electrodes 107 to 109 to be lowered in amounts similar to electrodes 100 to 105 without interfering with the wave-

length selectivity. When the current passing through the electrode 106 is the maximum which can be applied to reduce n, and thus the maximum amount of fine adjustment has occurred, the electrodes 100 to 105 will be passing a current which corresponds to half of the total reduction of n in the material in section 62 below electrodes 100 to 105.

[0085] To further adjust the wavelength at which the grating reflects, the current is removed from electrode 106 and is applied to the next adjacent electrode (or any other selected electrode) and the sequence of actions is repeated. By this means the grating can be adjusted over the entire 1530nm to 1570nm waveband.

[0086] The selectivity of the chirp at a particular wavelength can be enhanced as shown schematically in Fig 12. This figure is similar to Fig 11 but shows what happens when two adjacent sections of the chirp grating are moved together.

[0087] In the upper portion of Fig 12 the chirp grating is shown in the same position as in Fig 11. This is also the case for the central portion of Fig 12, where current applied to electrode 106 has caused a lowering of the line 111 to the position half way down to its maximum extent. If the current is passed through electrode 105 this causes the line 113 to be lowered and the current passing through electrode 106 is increased at the same rate so that lines 111 a and 113 move down in synchronism. This means that the grating selectivity is increased by the enhanced reflectivity.

[0088] When the applied current to electrode 105 is half of that applied to electrode 106 and the line 111 a is depressed to its maximum extent the lines 111 a and 113 will also coincide with portion 114 of line 110 to give a three-region coincidence.

[0089] It will be appreciated that the more electrodes that can be installed over the chirp, the greater the number of regions that can be brought into coincidence and the smaller each reduction in n needed at any point to adjust the chirp. For a range of 40 nm total adjustment, if say, twelve different electrode positions were used, then each would only be required to adjust through a range of 4 nm to cover the entire band with a degree of wavelength margin at the band edges.

[0090] The inter-relationship of the front and rear reflectors is most easily understood with reference to Fig. 13.

[0091] These drawings in Fig 13 show one above the other the combs of reflectance produced by the front and rear reflectors. In the drawings the intensity of reflectance I is plotted vertically against wavelength λ . Fig 13a shows the intensity of reflectance (reflectivity) I produced by the chirped grating beneath electrodes 65 to 72 in its passive condition i.e. no current applied to electrodes 65 through 72. This substantially uniform reflectivity 200 is positioned directly over the comb of reflectances 65a to 72a shown in Fig 13b, which is produced by the rear grating 51 in the laser of Figure 3. The smoothness of the reflectivity profile shown in Figure 13a is idealised and in prac-

tice will have structure associated with manufacturing tolerances. This structure, and any noise, will be significantly smaller in intensity compared to the controlled peaks which will be created in the front and rear reflectors.

[0092] If only just sufficient current is injected into the gain section to make it generate light, the laser will not lase because the intensity of the light at all of the wavelengths represented by the peaks 65a to 72a being the peaks from the rear reflector (and of course all other wavelengths) is below the lasing threshold.

[0093] To get the laser to lase predictably, it is necessary to have both a population inversion of charge carriers within the gain material and to get at least one, and preferably only one, wavelength to be above the lasing threshold. This is achieved by injecting sufficient current into the gain section 61 through electrode 64 to create the population inversion and by making a portion of the front grating reflect light of a specific wavelength preferentially, so that the rear grating selectively reflects light of that particular wavelength. The front grating will reflect back the light of that wavelength, so that that wavelength will become the preferred or enhanced wavelength and the laser will commence to lase at that wavelength.

[0094] This is carried out as follows.

[0095] The material of which layer 3 is formed in the sections 50 and 62 is such as to experience a reduction in refractive index when an electrical current is passed through it. If sufficient current is passed through electrode 68 to cause the wavelength of reflectivity of the grating below that electrode to superimpose and reinforce with the reflectivity of the grating below electrode 67 then a reflectivity peak 201 in the front reflector response is produced as shown in Fig 13c.

[0096] Now if current is also passed through the electrode 64 to create light in the gain section 61 at an intensity above the lasing threshold, the light at a wavelength corresponding to the peak 201 is selectively reinforced and the laser will commence to lase at the wavelength E as shown in Fig 13d. Thus the laser will be tuned to that wavelength. An advantage of this laser design is that the breadth of the front mirror peak can be sufficiently broad that tuning may be affected solely by the rear grating tuning current, within the wavelength window defined by the broad front mirror peaks.

[0097] If a current is now passed through electrode 52 this will move the whole comb of peaks 65a to 72a including peak F to lower wavelengths as shown in Fig 13e. The peak F will have a slightly reduced intensity compared to peak E because the maxima of the peaks of the front and rear reflectors are no longer exactly aligned.

[0098] If at the same time a current is passed through electrode 67 and the current passing through electrode 68 is increased, then the peak 201 in Fig 13c will also move to a lower wavelength and thus the maxima of the peaks of the front and rear reflectors can be brought back into exact alignment.

[0099] Thus the laser can be fine tuned to lase at wave-

lengths between the peaks 65a to 72a as shown in Fig 13b.

[0100] It will be appreciated that the peak 201 cannot exist effectively at the extreme long wavelength end of the chirped Bragg grating corresponding to the grating below electrode 72 of Figure 3.

[0101] To ensure complete band coverage out of band, or edge-of-band, segments can be employed. The long wavelength out-of-band segment being provided with a tuning electrode so that it can, by means of current injection, be driven to coincide with the first in-band long wavelength segment. The short wavelength out-of-band segment does not of necessity need to be provided with an electrode, as its operation at this lasing wavelength, is determined by driving current into the shortest wavelength in-band segment. The short wavelength out-of-band segment does need to be provided with an electrode if required to be fine tuned. Incorporation of these out-of-band, or edge-of-band segments allows for production spread in operating characteristics and helps improve production yields.

[0102] With InP, as a typical Group III-V laser material the reduction in material refractive index through current injection permits wavelength tuning in the range of 1 - 10nm. Using such material the tuning segments will typically be designed at 4nm wavelength spacing. With such an arrangement to produce coincidence with its next lowest wavelength neighbour requires 4nm wavelength shift of a segment, whilst leaving a further 4nm coincident tuning capability. By this means the whole band of interest may be covered.

[0103] The lasers as set out in the embodiments do not have a constant cavity length as they go from one supermode to another, which can result in mode hopping if great care is not taken to avoid it. The function of the phase change section 60 is to compensate for these variations in the optical path length as the laser is tuned. The section 60 is also formed of a material which will reduce in refractive index when a current is passed through it, and current can be passed through electrode 63 to affect such a change.

[0104] Thus the laser of the invention is capable of coarse tuning from one peak 65a to 72a as shown in Fig 13b and also fine-tuning of the peaks to lower wavelengths in a simple and effective manner.

[0105] Although the above description refers to the use of a phase shifted grating distributed Bragg reflector for the rear mirror, a sampled segmented grating distributed Bragg reflector could be used. A phase shifted grating distributed Bragg reflector is preferred because the reflection peaks of the comb produced by such a distributed Bragg reflector is substantially flat and uniform. With a sampled segmented grating distributed Bragg reflector, as utilised in US-A-4 896 325, on the other hand the reflection spectrum has a Sinc squared envelope, which means that the lasers with such an output distribution cannot be reliably operated over such a wide optical bandwidth as those using a phase shifted grating distrib-

uted Bragg reflector as the rear mirror.

[0106] In normal operation light output is coupled from the front of the laser adjacent to the gain section, and a small amount of light maybe taken from the rear of the laser adjacent the Bragg grating(s) for auxiliary purposes such as wavelength locking. However, nothing is meant to imply that implementations with light primarily coupled out of the rear of the laser are precluded from the scope of the invention.

[0107] It is preferred that the reflectivity of the rear mirror be as high as possible, typically in the range 50% to 80%. On the other hand the reflectivity of the front mirror should be lower, and typically in the range 20% to 40%.

Claims

1. A tuneable laser having a gain section (4) bounded at one end by a first reflector (7) in the form of a distributed Bragg reflector adapted to produce a comb of reflective peaks and at the other end by a second Bragg reflector (6), the second Bragg reflector adapted to reflect at a plurality of wavelengths, discrete segments (9-16) of the second Bragg reflector being capable of being tuned selectively so that one or more segments (9-16) of the second Bragg reflector (6) can be tuned to a lower wavelength to reflect with a segment of the second Bragg reflector reflecting at that lower wavelength to enhance the reflectivity at that lower wavelength, the lower wavelength to which the second reflector is tuned substantially coinciding with a peak of the first reflector, thereby to cause the laser to lase at that lower wavelength,
2. A tuneable laser as claimed in claim 1, in which the second reflector is formed in a material having a variable refractive index and in which the tuning of the reflected wavelength is effected by varying the refractive index of the material.
3. A tuneable laser as claimed in claim 2, in which the refractive index is varied by passing an electrical current through the material in which the second reflector is formed.
4. A tuneable laser as claimed in claim 3, in which the second Bragg reflector is a chirped grating and is formed in a material having a refractive index variable in response to the passage of current there-through, there being a plurality of external electrodes along the length of the grating, with each electrode being selectively connectable to a power source.
5. A tuneable laser as claimed claim 4, in which the chirped Bragg reflector comprises a linear chirp of progressive pitch variation along the chirp with the shortest pitch closest to the gain section.
6. A tuneable laser as claimed in claim 4 or claim 5, in which the chirped Bragg reflector is partitioned into chirp segments each consisting of part of the over all chirp grating, all chirp segments being concatenated.
7. A tuneable laser as claimed in claim 3, in which the second Bragg reflector comprising a plurality of discrete grating segments, at least two of which grating segments have a different pitch wherein current is applicable to at least the grating having a longer pitch such that the effective wavelength of the grating having a longer pitch can be tuned to the wavelength of the grating having a shorter pitch.
8. A tuneable laser according to claim 3, wherein the second Bragg reflector comprises a plurality of discrete grating segments, each grating segment having a different pitch, such that the grating segment closest to the gain section has the shortest pitch, the pitch of each successive grating segment from the gain section being greater than the pitch of the preceding segment.
9. A tuneable laser according to claim 8, wherein each grating segment has an independently actuatable electrode.
10. A tuneable laser according to any one of claims 3 to 9, wherein a switching circuit is provided to switch the current to the electrodes.
11. A tuneable laser according to any one of claims 1 to 10, manufactured using semiconductor materials.
12. A tuneable laser according to claim 11, manufactured using a III-V semiconductor material.
13. A tuneable laser according to any one of claims 1 to 12, manufactured using electron beam writing techniques.
14. A tuneable laser according to any one of claims 1 to 13, manufactured using a holographic phase grating plate.
15. A tuneable laser as claimed in any one of the preceding claims in which the Bragg segments in the second reflector are each kept short as herein defined so that the cumulative waveguide length associated with the Bragg gratings is minimised, thereby keeping the waveguide losses low.
16. A tuneable laser as claimed in any one of the preceding claims in which the distributed Bragg reflector forming the first reflector is a phase shifted Bragg grating reflector.

17. A tuneable laser as claimed in claim 16, in which the first reflector has as many repeat grating units, as are required to produce sufficiently narrow peaks for single longitudinal mode operation of the laser, preferably 10 or more.
18. A tuneable laser as claimed in any one of the preceding claims in which light is emitted through the second reflector.
19. A tuneable laser as claimed in any one of the preceding claims in which there is a phase change section between the gain section and either one or both of the reflectors.
20. A tuneable laser as claimed in claim 19, in which the phase change section is located between the gain section and the first or second reflector.
21. A tuneable laser as claimed in claim 20, in which the phase change section(s) has an electrode(s) to permit passage of current through the phase change section(s) to alter the refractive index of the material of the phase change section(s) to effect the phase change.

Patentansprüche

1. Abstimmbarer Laser mit einem Verstärkungsteil (4), der an einem Ende durch einen Reflektor (7) in Form eines verteilten Bragg-Reflektors mit der Aufgabe, einen Kamm von reflektierenden Peaks zu erzeugen, und am anderen Ende durch einen zweiten Bragg-Reflektor (6) begrenzt ist, wobei der zweite Bragg-Reflektor die Aufgabe hat, bei einer Mehrzahl von Wellenlängen zu reflektieren, wobei diskrete Segmente (9 - 16) des zweiten Bragg-Reflektors selektiv so abgestimmt werden können, dass ein oder mehrere Segmente (9 - 16) des zweiten Bragg-Reflektors (6) auf eine kleinere Wellenlänge abgestimmt werden können, um mit einem Segment des zweiten Bragg-Reflektors zu reflektieren, der bei dieser kleineren Wellenlänge reflektiert, um das Reflexionsvermögen bei dieser kleineren Wellenlänge zu erhöhen, wobei die kleinere Wellenlänge, auf die der zweite Reflektor abgestimmt ist, im Wesentlichen mit einem Peak des ersten Reflektors zusammenfällt, um **dadurch** zu bewirken, dass der Laser bei dieser kleineren Wellenlänge lasert.
2. Abstimmbarer Laser nach Anspruch 1, in dem der zweite Reflektor aus einem Material mit einem variablen Brechungsindex gebildet ist und wobei das Abstimmen der reflektierten Wellenlänge durch Variieren des Brechungsindex des Materials erfolgt.
3. Abstimmbarer Laser nach Anspruch 2, in dem der Brechungsindex durch Leiten eines elektrischen Stroms durch das Material variiert wird, in dem der zweite Reflektor ausgebildet ist.
4. Abstimmbarer Laser nach Anspruch 3, in dem der zweite Bragg-Reflektor ein Chirp-Gitter ist und aus einem Material mit einem Brechungsindex gebildet ist, der als Reaktion auf den Fluss von Strom **dadurch** variabel ist, wobei eine Mehrzahl von externen Elektroden entlang der Länge des Gitters vorhanden ist, wobei jede Elektrode selektiv mit einer Stromquelle verbunden werden kann.
5. Abstimmbarer Laser nach Anspruch 4, in dem der Chirp-Bragg-Reflektor einen linearen Chirp mit progressiver Teilungsvariation über den Chirp mit der kürzesten Teilung umfasst, die dem Verstärkungsteil am nächsten liegt.
6. Abstimmbarer Laser nach Anspruch 4 oder Anspruch 5, in dem der Chirp-Bragg-Reflektor in Chirp-Segmente partitioniert ist, die jeweils aus einem Teil des gesamten Chirp-Gitters bestehen, wobei alle Chirp-Segmente verkettet sind.
7. Abstimmbarer Laser nach Anspruch 3, in dem der zweite Bragg-Reflektor eine Mehrzahl von diskreten Gittersegmenten umfasst, wobei wenigstens zwei dieser Gittersegmente eine andere Teilung haben, wobei Strom wenigstens dem Gitter mit längerer Teilung zugeführt werden kann, so dass die effektive Wellenlänge des Gitters mit längerer Teilung auf die Wellenlänge des Gitters mit kürzerer Teilung abgestimmt werden kann.
8. Abstimmbarer Laser nach Anspruch 3, wobei der zweite Bragg-Reflektor eine Mehrzahl von diskreten Gittersegmenten umfasst, wobei jedes Gittersegment eine andere Teilung hat, so dass das Gittersegment, das dem Verstärkungsteil am nächsten liegt, die kürzeste Teilung hat, wobei die Teilung jedes aufeinander folgenden Gittersegmentes vom Verstärkungsteil größer ist als die Teilung des vorherigen Segments.
9. Abstimmbarer Laser nach Anspruch 8, wobei jedes Gittersegment eine unabhängig zu betätigende Elektrode hat.
10. Abstimmbarer Laser nach einem der Ansprüche 3 bis 19, wobei eine Schaltung vorgesehen ist, um den Strom zu den Elektroden zu schalten.
11. Abstimmbarer Laser nach einem der Ansprüche 1 bis 10, der mit Halbleitermaterialien hergestellt wurde.
12. Abstimmbarer Laser nach Anspruch 11, der mit ei-

nem Halbleitermaterial der Gruppe III-V hergestellt wurde.

13. Abstimmbarer Laser nach einem der Ansprüche 1 bis 12, der mit Elektronenstrahlenschreibtechniken hergestellt wurde. 5
14. Abstimmbarer Laser nach einem der Ansprüche 1 bis 13, der mit einer holografischen Phasengitterplatte hergestellt wurde. 10
15. Abstimmbarer Laser nach einem der vorherigen Ansprüche, in dem die Bragg-Segmente im zweiten Reflektor jeweils kurz wie hierin definiert gehalten werden, so dass die kumulative Wellenleiterlänge in Verbindung mit den Bragg-Gittern minimiert wird, um Wellenleiterverluste niedrig zu halten. 15
16. Abstimmbarer Laser nach einem der vorherigen Ansprüche, in dem der den ersten Reflektor bildende verteilte Bragg-Reflektor ein phasenverschobener Bragg-Gitterreflektor ist. 20
17. Abstimmbarer Laser nach Anspruch 16, in dem der erste Reflektor so viele Wiederholungsgittereinheiten hat, wie zum Erzeugen von ausreichend engen Peaks für einen Einzellängsmodenbetrieb des Lasers benötigt wird, vorzugsweise 10 oder mehr. 25
18. Abstimmbarer Laser nach einem der vorherigen Ansprüche, in dem Licht durch den zweiten Reflektor emittiert wird. 30
19. Abstimmbarer Laser nach einem der vorherigen Ansprüche, in dem ein Phasenänderungsteil zwischen dem Verstärkungsteil und einem oder beiden der Reflektoren vorhanden ist. 35
20. Abstimmbarer Laser nach Anspruch 19, in dem sich der Phasenänderungsteil zwischen dem Verstärkungsteil und dem ersten oder zweiten Reflektor befindet. 40
21. Abstimmbarer Laser nach Anspruch 20, in dem der/die Phasenänderungsteil(e) (eine) Elektrode(n) hat/haben, um den Fluss von Strom durch den/die Phasenänderungsteil(e) zuzulassen, um den Brechungsindex des Materials des/der Phasenänderungsteils/e zu ändern, um die Phasenänderung zu bewirken. 45

Revendications

1. Laser accordable ayant une partie gain (4) délimitée à une extrémité par un premier réflecteur (7) sous la forme d'un réflecteur de Bragg réparti adapté pour produire un peigne de pics réfléchissants et à l'autre 55

extrémité par un deuxième réflecteur de Bragg (6), lequel deuxième réflecteur de Bragg est adapté pour réfléchir à une pluralité de longueurs d'ondes, des segments discrets (9-16) du deuxième réflecteur de Bragg pouvant être accordés sélectivement de telle sorte qu'un ou plusieurs segments (9-16) du deuxième réflecteur de Bragg (6) peuvent être accordés à une longueur d'onde plus basse pour réfléchir avec un segment du deuxième réflecteur de Bragg qui réfléchit à cette longueur d'onde plus basse pour renforcer la réflectivité à cette longueur d'onde plus basse, la longueur d'onde plus basse à laquelle est accordé le deuxième réflecteur coïncidant sensiblement avec un pic du premier réflecteur, si bien que le laser produit son effet à cette longueur d'onde plus basse.

2. Laser accordable selon la revendication 1, dans lequel le deuxième réflecteur est formé d'un matériau ayant un indice de réfraction variable et dans lequel l'accord de la longueur d'onde réfléchie est effectué par variation de l'indice de réfraction du matériau.
3. Laser accordable selon la revendication 2, dans lequel l'indice de réfraction est modifié par le passage d'un courant électrique dans le matériau formant le deuxième réflecteur.
4. Laser accordable selon la revendication 3, dans lequel le deuxième réflecteur de Bragg est un réseau gravé à chirp et est formé d'un matériau ayant un indice de réfraction variable en réponse au passage du courant qui le traverse, une pluralité d'électrodes extérieures étant situées sur la longueur du réseau gravé, chaque électrode étant connectable sélectivement à une source de courant électrique.
5. Laser accordable selon la revendication 4, dans lequel le réflecteur de Bragg à chirp comprend un chirp linéaire à variation de pas progressive le long du chirp, le pas le plus court étant le plus proche de la partie gain.
6. Laser accordable selon la revendication 4 ou 5, dans lequel le réflecteur de Bragg à chirp est découpé en segments de chirp dont chacun est constitué d'une partie du réseau gravé à chirp global, tous les segments de chirp étant concaténés.
7. Laser accordable selon la revendication 3, dans lequel le deuxième réflecteur de Bragg comprend une pluralité de segments de réseau gravé discrets, au moins deux desdits segments de réseau gravé ayant un pas différent dans lequel le courant est applicable au moins au réseau gravé ayant un pas plus long, de telle sorte que la longueur d'onde effective du réseau gravé ayant un pas plus long peut être accordée à la longueur d'onde du réseau gravé ayant

un pas plus court.

8. Laser accordable selon la revendication 3, dans lequel le deuxième réflecteur de Bragg comprend une pluralité de segments de réseau gravé discrets, chaque segment de réseau gravé ayant un pas différent, de telle sorte que le segment de réseau gravé le plus proche de la partie gain a le pas le plus court, le pas de chaque segment de réseau gravé successif à partir de la partie gain étant plus grand que le pas du segment précédent. 5
9. Laser accordable selon la revendication 8, dans lequel chaque segment de réseau gravé a une électrode actionnable indépendamment. 10
10. Laser accordable selon l'une quelconque des revendications 3 à 19, dans lequel un circuit de commutation est prévu pour commuter le courant aux électrodes. 15
11. Laser accordable selon l'une quelconque des revendications 1 à 10, fabriqué avec des matériaux semi-conducteurs. 20
12. Laser accordable selon la revendication 11, fabriqué avec un matériau semi-conducteur III-V. 25
13. Laser accordable selon l'une quelconque des revendications 1 à 12, fabriqué en employant des techniques d'écriture par faisceau d'électrons. 30
14. Laser accordable selon l'une quelconque des revendications 1 à 13, fabriqué en employant une plaque de réseau gravé à phase holographique. 35
15. Laser accordable selon l'une quelconque des revendications précédentes, dans lequel les segments de Bragg dans le deuxième réflecteur sont maintenus courts comme défini ici, de telle sorte que la longueur de guide d'onde cumulative associée avec les réseaux de Bragg soit minimisée, en réduisant ainsi les pertes de guide d'onde. 40
16. Laser accordable selon l'une quelconque des revendications précédentes, dans lequel le réflecteur de Bragg réparti formant le premier réflecteur est un réflecteur à réseau de Bragg déphasé. 45
17. Laser accordable selon la revendication 16, dans lequel le premier réflecteur a autant d'unités de réseau répétées que nécessaire pour produire des pics suffisamment étroits pour le fonctionnement en mode longitudinal unique du laser, de préférence 10 ou davantage. 50
18. Laser accordable selon l'une quelconque des revendications précédentes, dans lequel une lumière est 55

émise à travers le deuxième réflecteur.

19. Laser accordable selon l'une quelconque des revendications précédentes, dans lequel il y a une section à changement de phase entre la partie gain et l'un des réflecteurs ou les deux.
20. Laser accordable selon la revendication 19, dans lequel la section à changement de phase est située entre la partie gain et le premier ou le deuxième réflecteur.
21. Laser accordable selon la revendication 20, dans lequel la ou les sections à changement de phase ont une ou plusieurs électrodes pour permettre le passage du courant dans la ou les sections à changement de phase pour modifier l'indice de réfraction du matériau de la ou des sections à changement de phase de manière à réaliser le changement de phase.

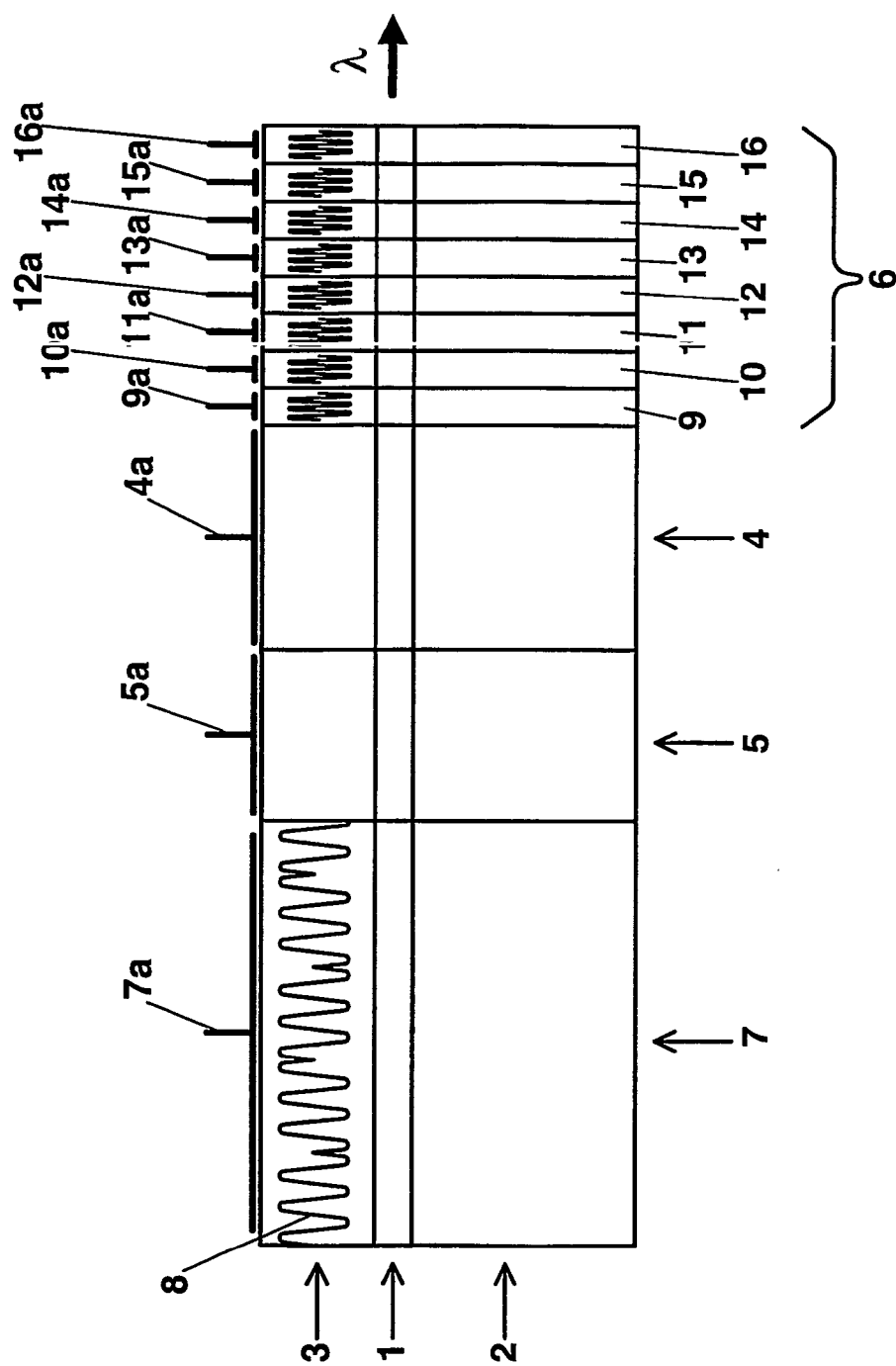
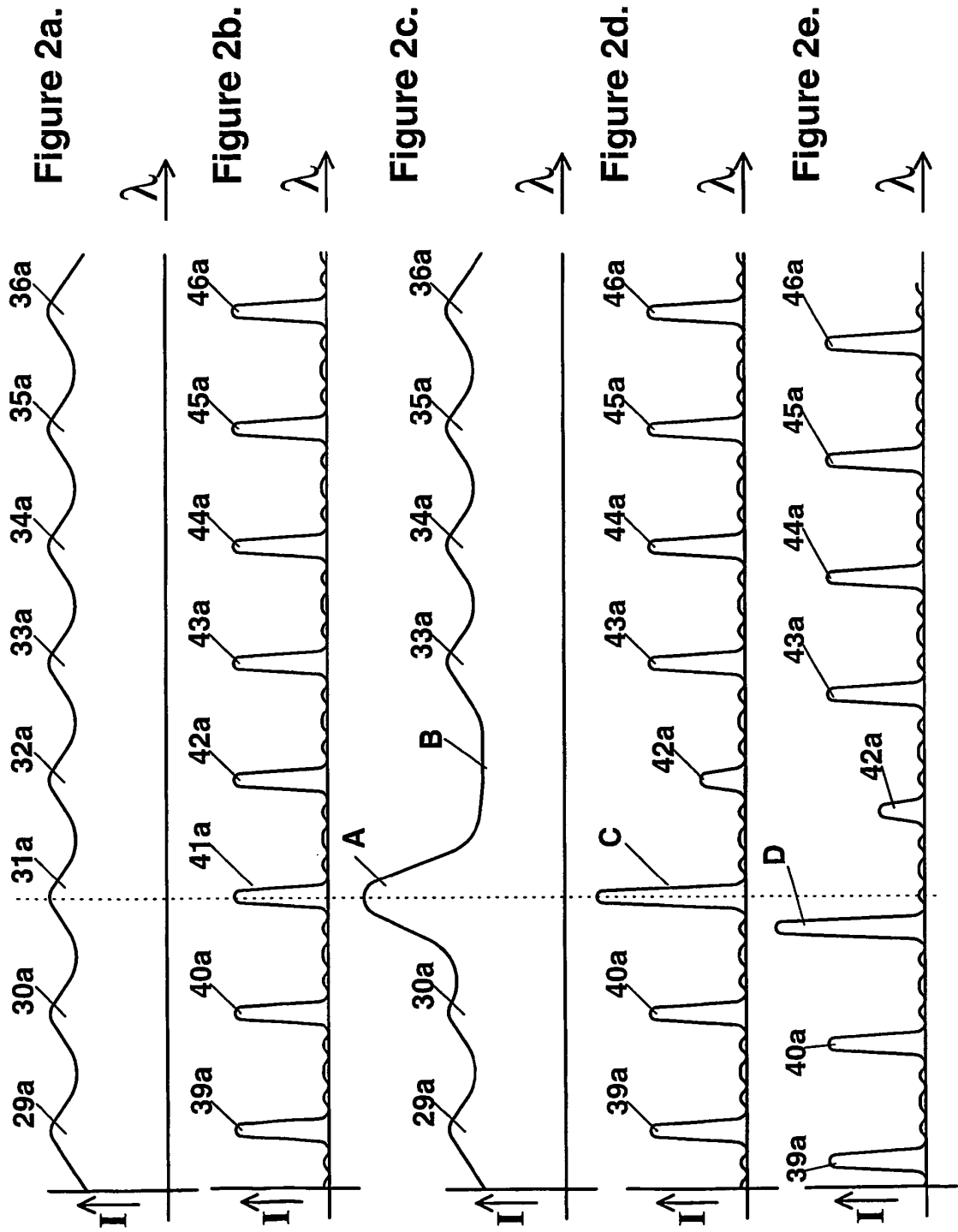


Figure 1.



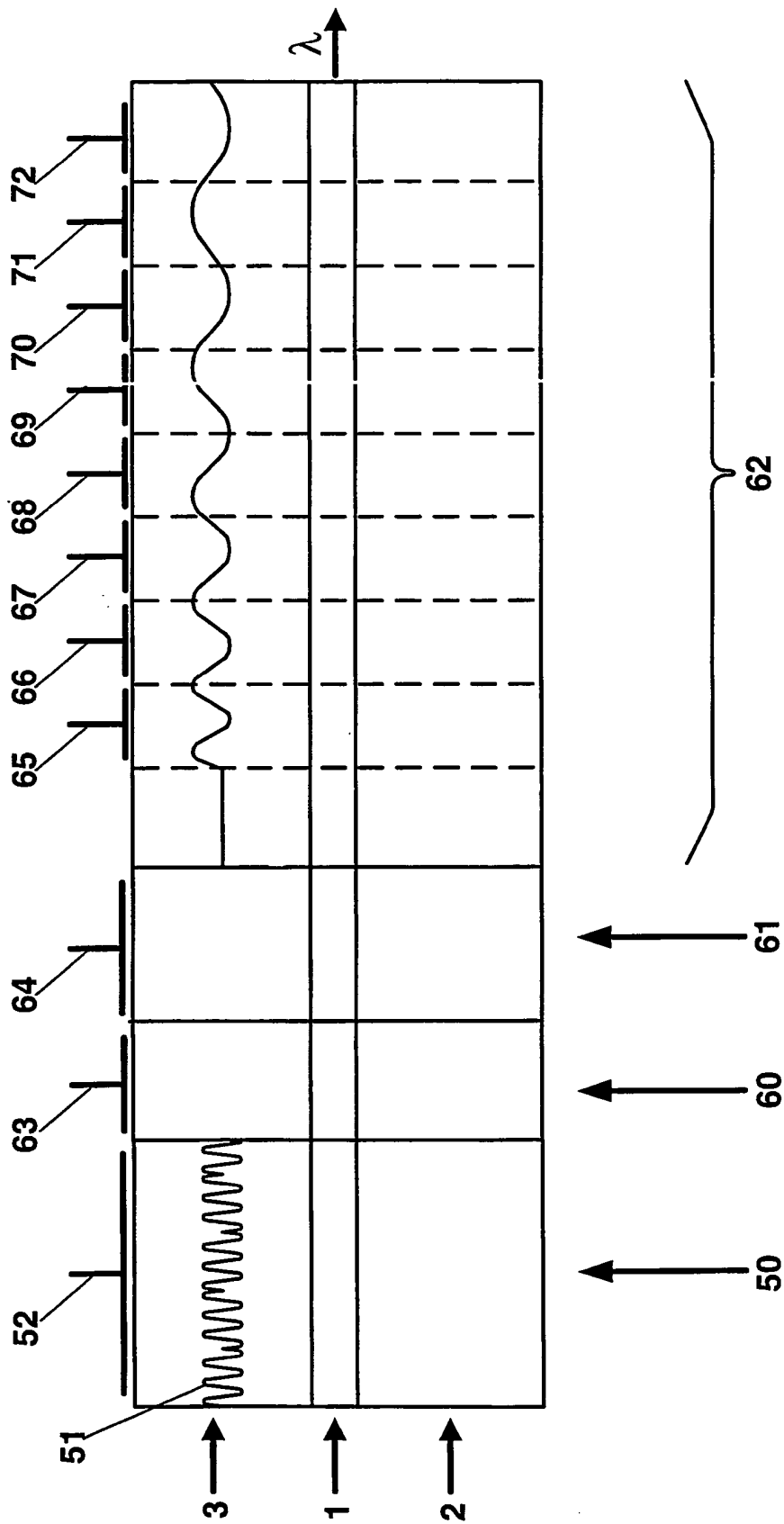


Figure 3.

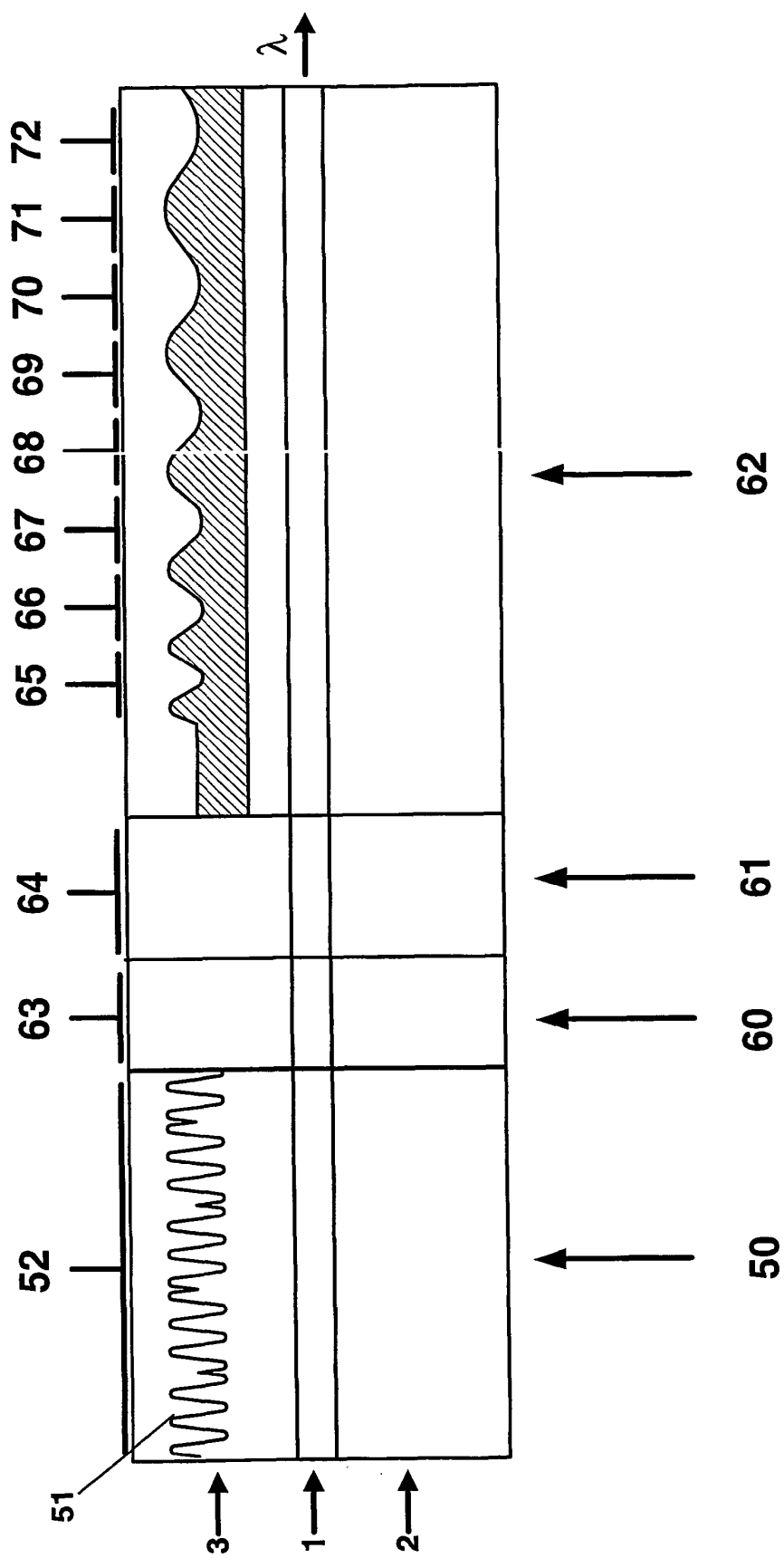


Figure 4.

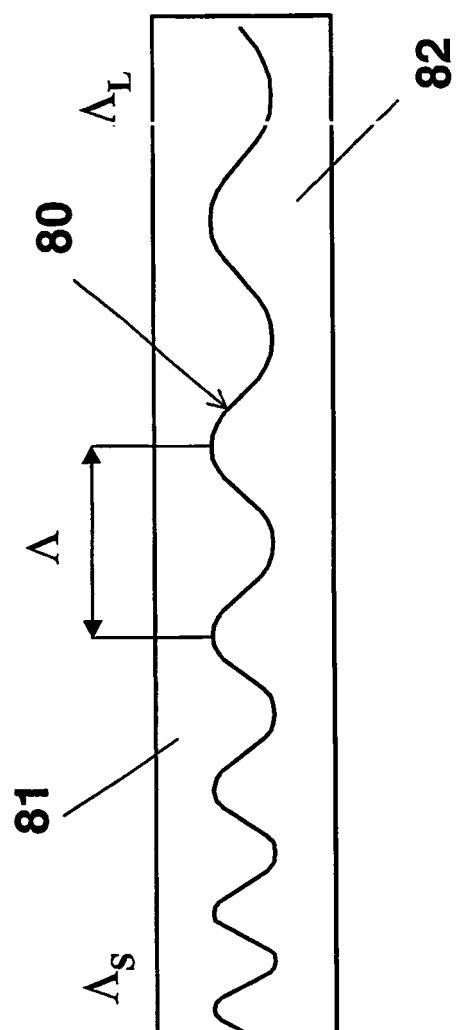


Figure 5.

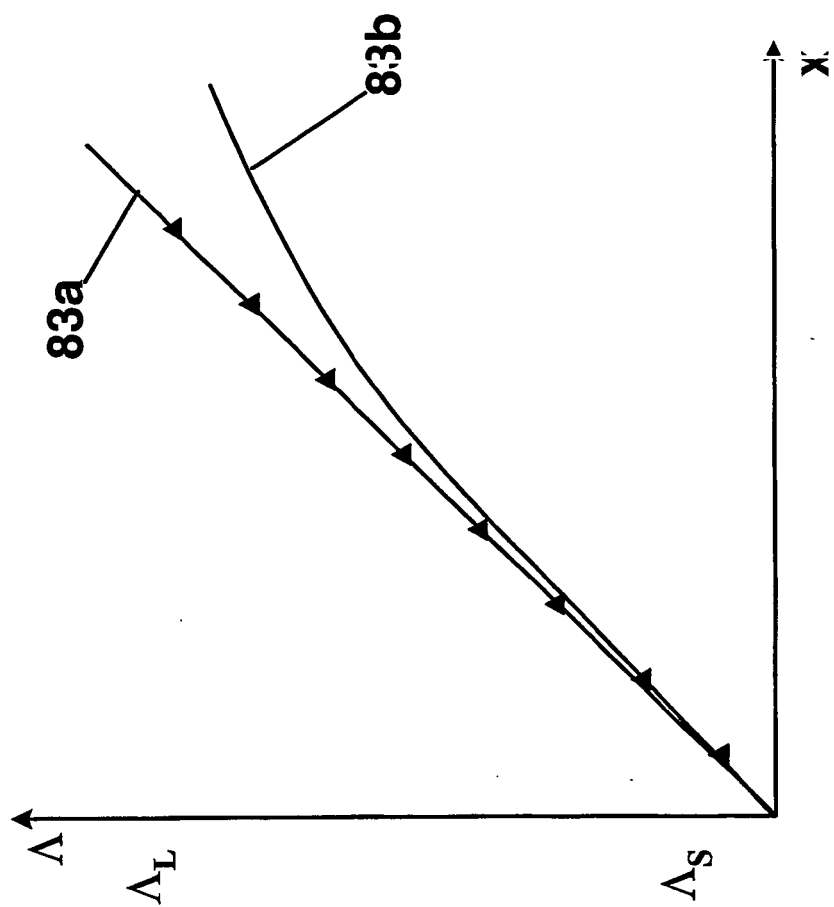


Figure 6.

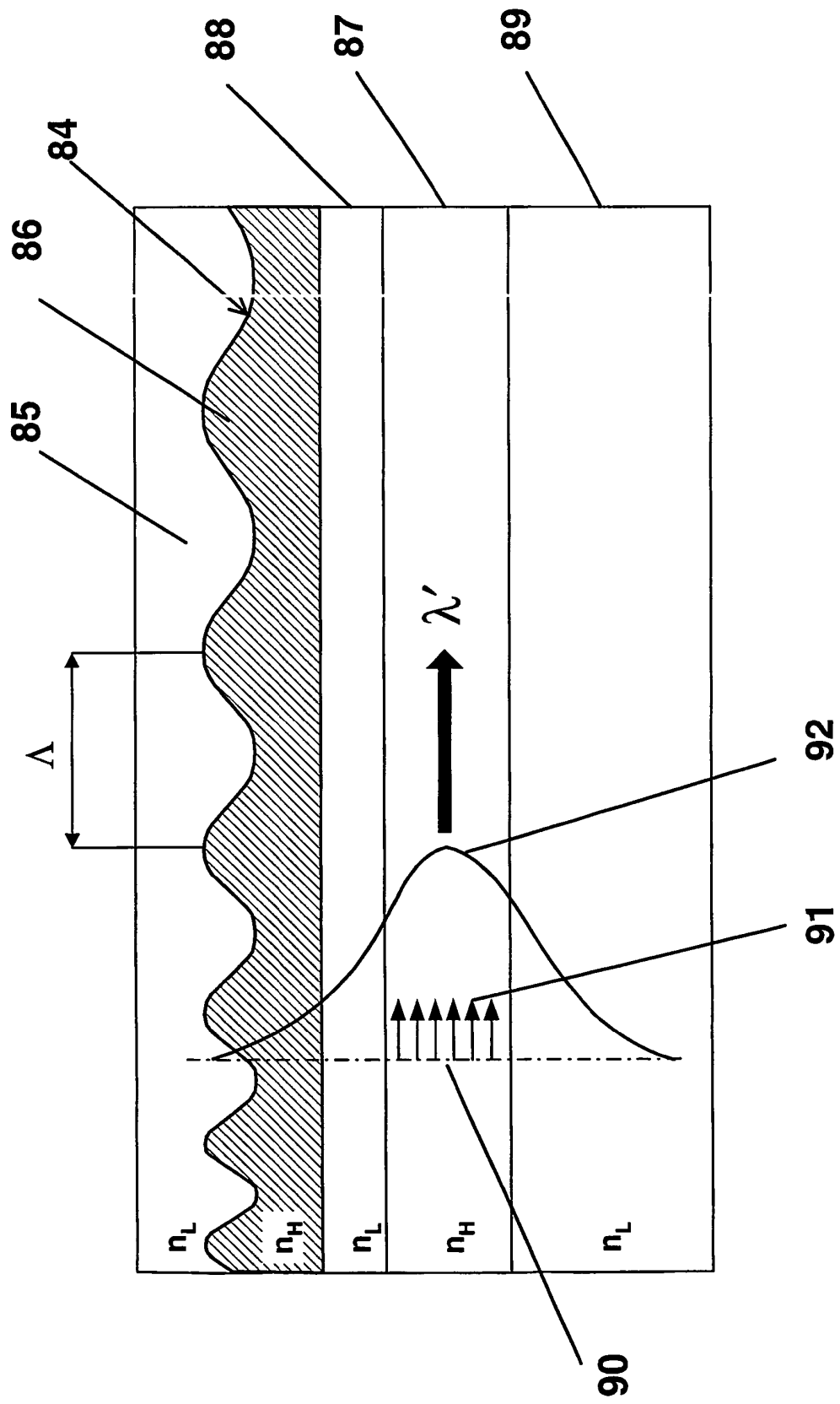


Figure 7.

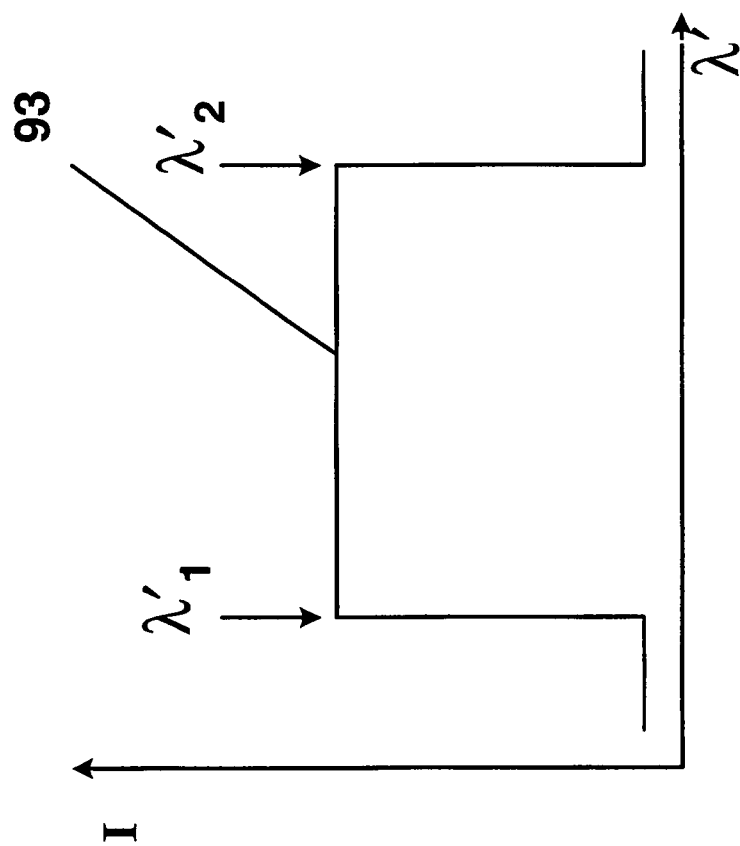


Figure 8.

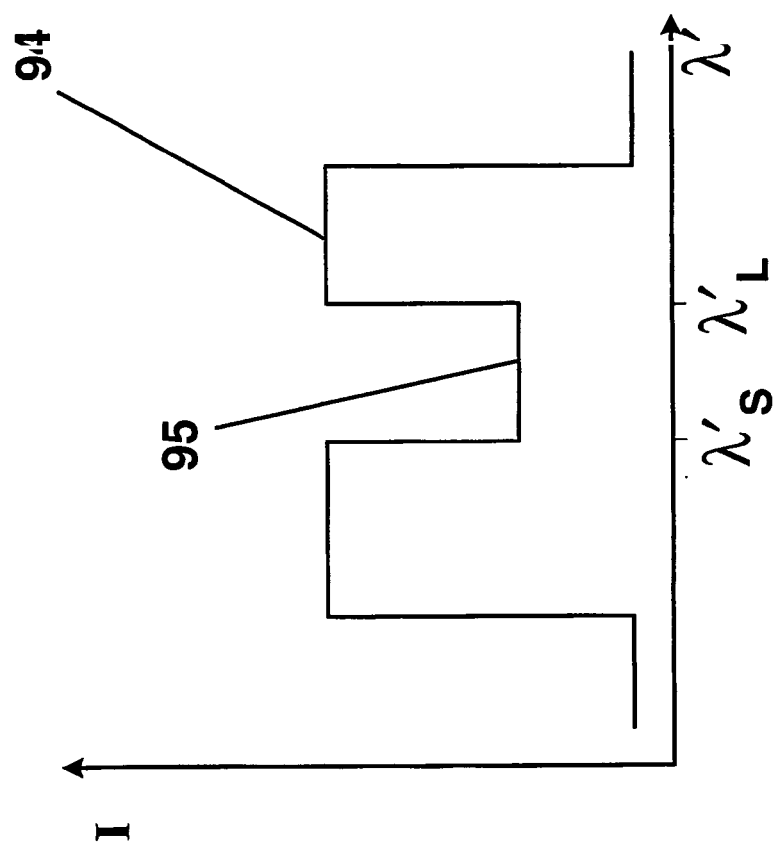


Figure 9.

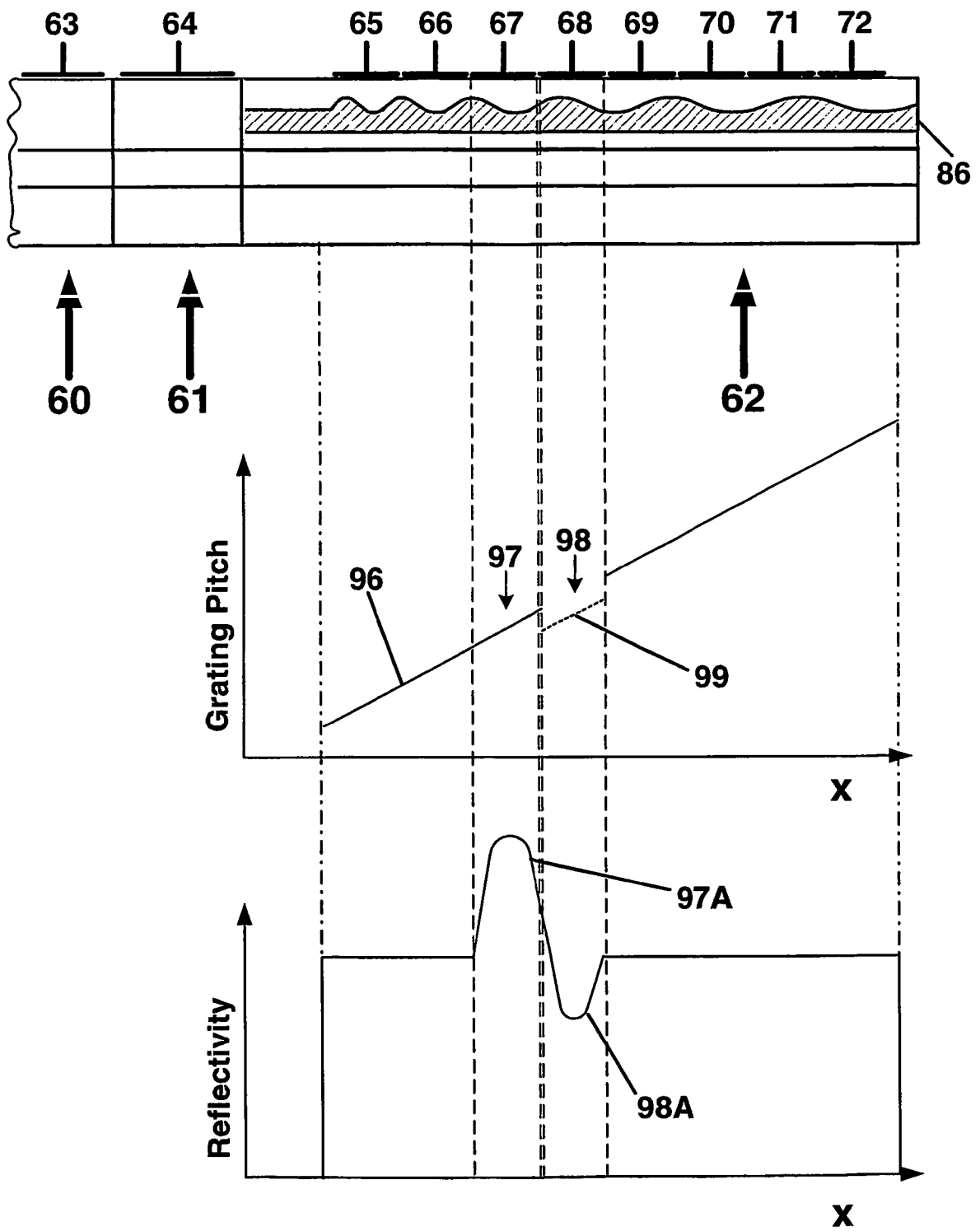


Figure 10.

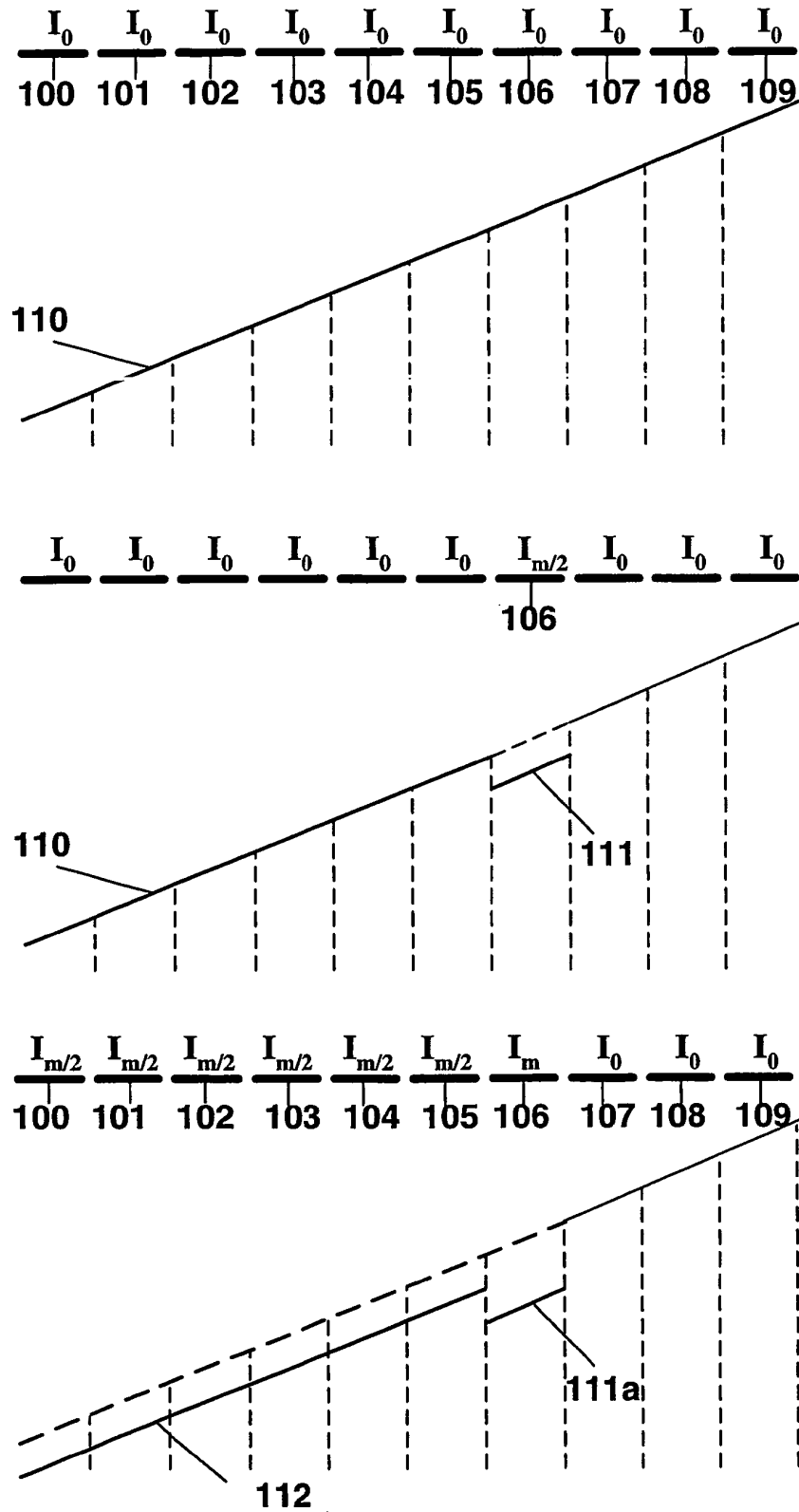


Figure 11.

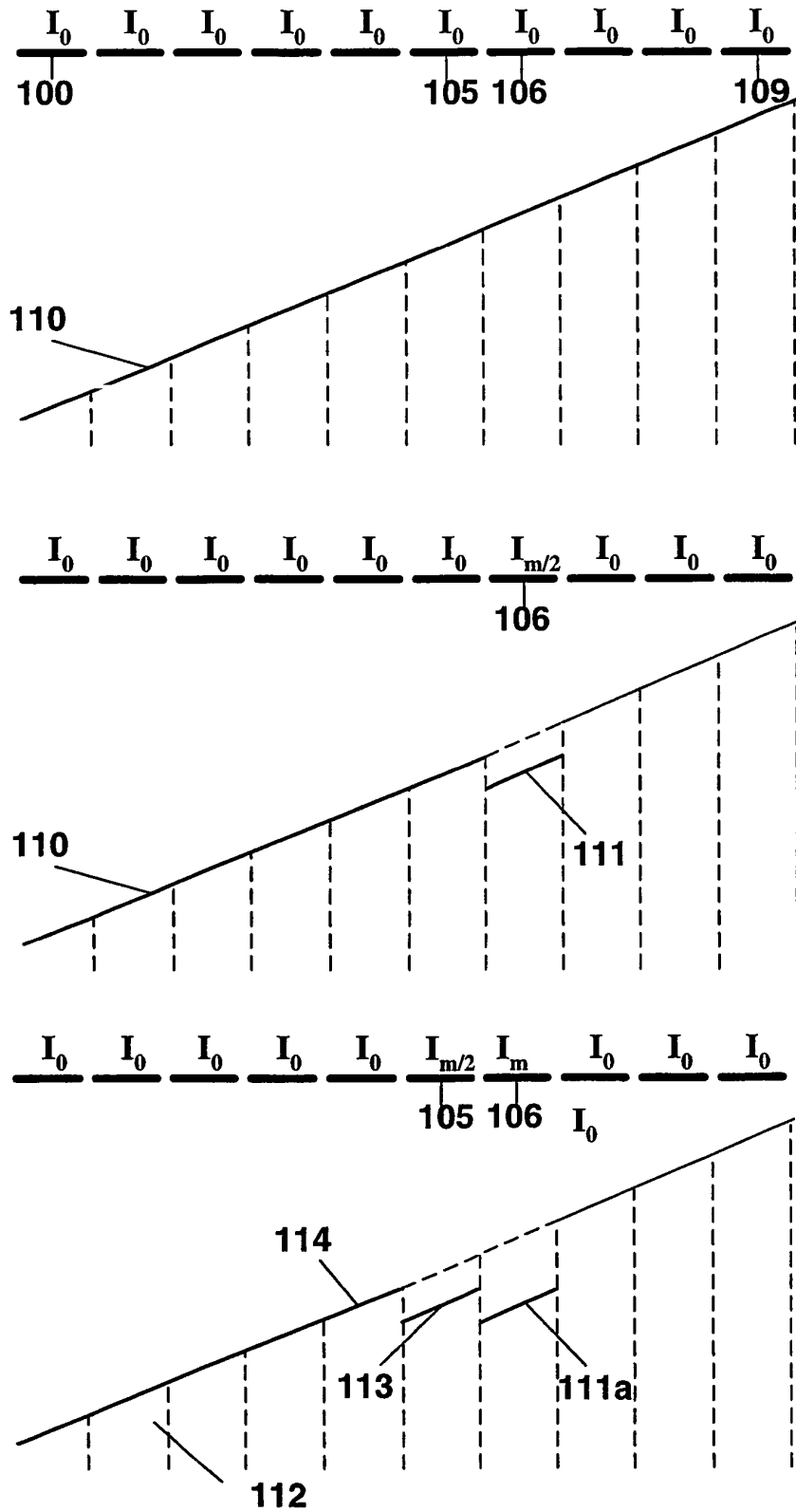


Figure 12.

Figure 13a.

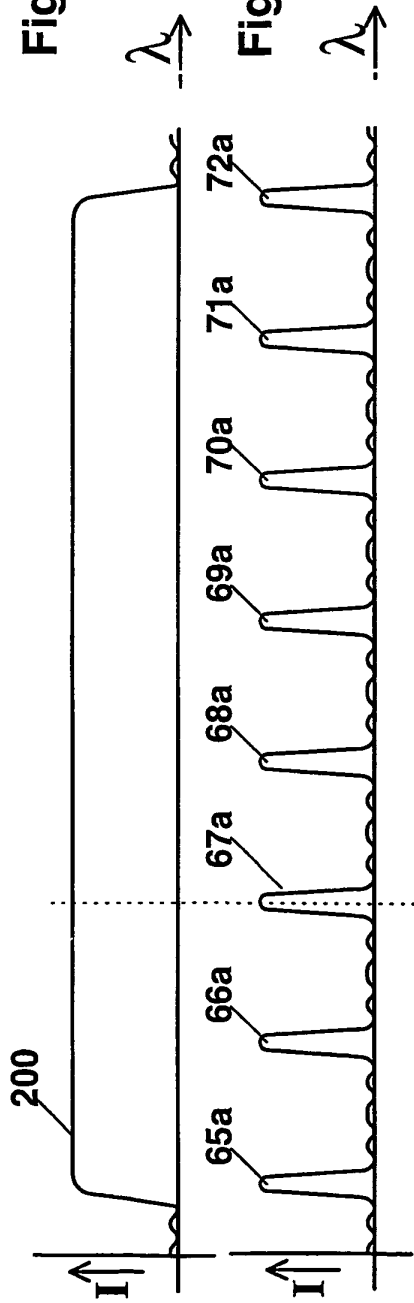


Figure 13b.



Figure 13c.

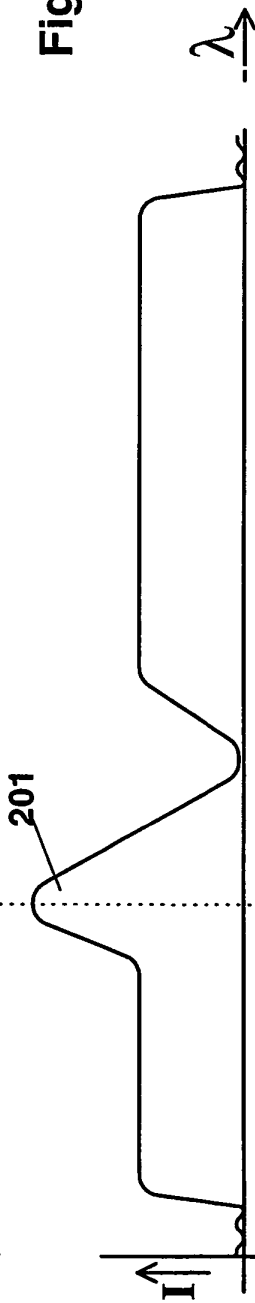


Figure 13d.

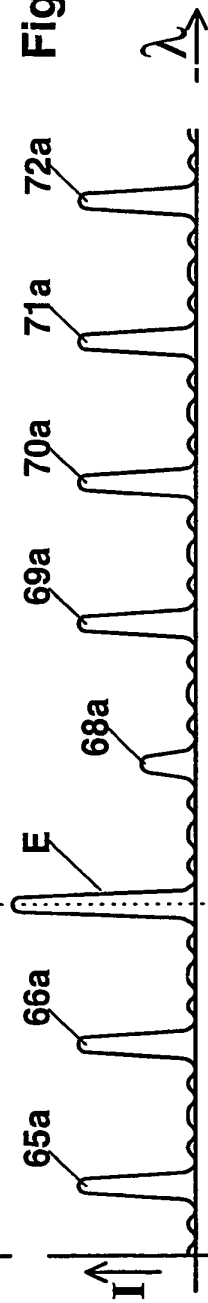
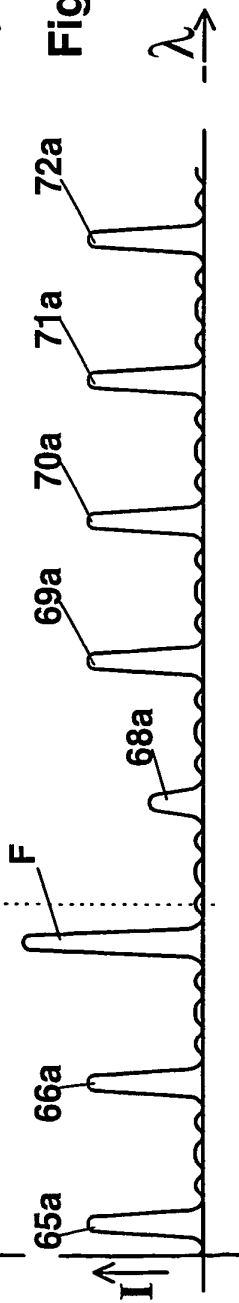


Figure 13e.



REFERENCES CITED IN THE DESCRIPTION

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